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Evolutionary Dynamics of Passive Housing Initiatives in New Rural Construction

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Abstract: In the context of China's ambitious dual carbon goals, this study introduces an innovative reward–penalty incentive mechanism, grounded in evolutionary game theory, to develop a tripartite evolutionary game model concerning the construction of passive rural housing. This research meticulously analyzes the equilibrium and stability strategies of all involved parties and employs data simulation to examine the influence of varying parameters on the game dynamics. Our findings reveal that the government's cost–benefit calculations significantly influence its decisions regarding passive housing initiatives. The study identifies optimal cost and benefit strategies for various developmental phases. Furthermore, the level of governmental rewards and penalties plays a crucial role in determining whether enterprises and farmers opt for passive housing solutions. The study establishes the efficacy of different incentive schemes at various stages. Importantly, the economic interests of enterprises and farmers are pivotal in their decision-making process regarding passive housing. The study advocates for a comprehensive set of measures to safeguard these interests, with a special emphasis on protecting farmers. In conclusion, this research offers substantial guidance for policy decisions aimed at transforming existing rural housing into passive housing, thereby aligning with China's environmental and sustainability objectives.

Keywords: passive housing; new rural construction; tripartite evolutionary game model; scenario simulation

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1. Introduction

In 2019, China's construction industry accounted for 33% of China's total energy consumption [1]. On 22 September 2020, at the general debate of the 75th session of the United Nations General Assembly, China announced its commitment to peak carbon emissions before 2030 and achieve carbon neutrality before 2060 [2]. In order to achieve this goal, energy efficiency in the construction sector has become one of the key areas of focus [3]. Since 2005, rural buildings in China have accounted for more than half of the total energy consumption of buildings, and even in the face of rapid urbanization, they are still expected to account for 25% by 2050 [3]. In order to reduce energy consumption in the construction sector, passive housing is gradually gaining attention. Passive housing is a type of low-energy building that is constructed by utilizing passive technology and incorporating local climate and other natural conditions [4]. Currently, the widely used passive building technology design includes building envelope structure design, ventilation system design, and the utilization of renewable energy, such as fresh air heat recovery systems and geothermal and solar energy utilization systems [5,6].

Regarding application examples, the Hamburg House in China utilizes a ground-source heat pump system, a photovoltaic power generation system, and automatic control window technology, saving energy by up to 90% [7,8]. The Bruck Passive House also adopts a solar hot water system, reclaimed water, variable frequency air-cooled heat pump, fresh air system, and dry cooling coil, achieving energy savings of up to 95% [9]. As mentioned above, similar completed cases show that passive houses are completely feasible in China. Compared to green-building forms of housing, passive houses have greater energy-saving potential and are an effective way to reduce building energy consumption and carbon emissions [10].

However, due to issues such as low construction quality and unknown investment returns, enterprises and farmers are unwilling to cooperate with passive housing implementation [11]. Therefore, the government should play a leading role in vigorously introducing incentives for passive housing to encourage enterprises and users to make different choices to pursue their own interests [12–14]. In the process of implementing incentive policies, the reward–penalty mechanism (RPM) is considered an effective incentive strategy for quality control in allocation systems. It is an effective way to reduce individual non-cooperative behavior and can promote cooperation in the long-term evolutionary process [15–17]. In the study of dynamic stakeholder decision making based on evolutionary game theory, the introduction of a reward–punishment mechanism can lead to better evolutionary outcomes.

This article was based on evolutionary game theory and the establishment of a reward–penalty mechanism to construct a game model between the government, enterprises, and farmers. The study analyzed the stable strategies of the three parties in the game, focusing on the relationship between reward and penalty systems and the relationship between cost and benefit in implementing passive housing to provide a reference for selecting rural passive housing construction strategies. The tripartite game relationship between the government, enterprises, and farmers is shown in Figure 1.

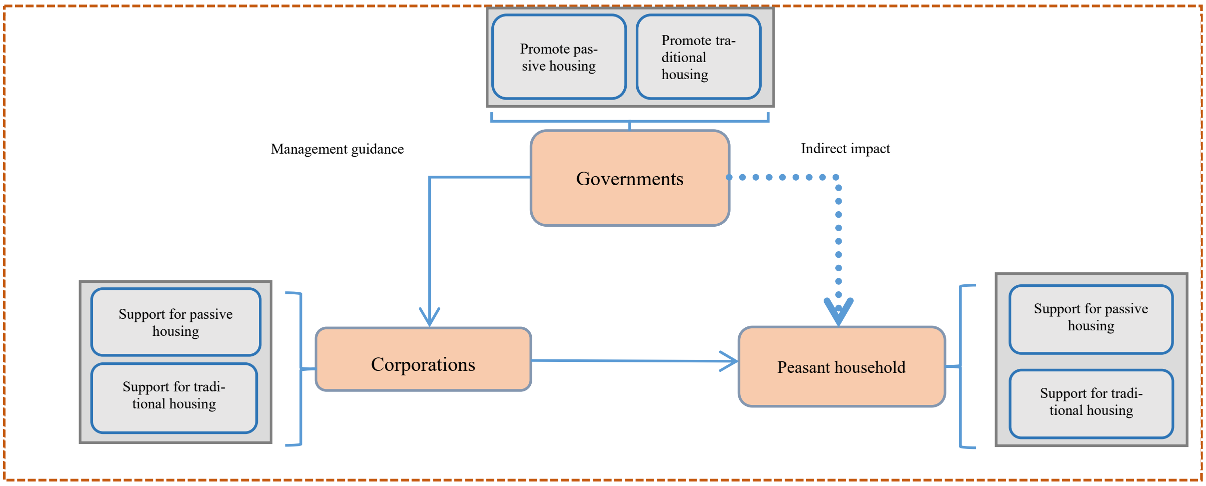


Figure 1. The tripartite game relationship between the government, enterprises, and farmers.

2. Construction of Dynamic Equations for Tripartite Games

2.1. Assumption Conditions Required for Constructing Dynamic Equations in the Tripartite Evolutionary Game

Game theory is the most influential economic analysis tool and decision theory model for understanding and analyzing conflicts and cooperation in the decision-making process. It fills the gaps left by traditional methods that overlook individual and social behavior [18]. Evolutionary game theory combines traditional game theory with dynamic evolution, using bounded rationality as the analytical framework [19,20]. By designing multi-party reward–penalty incentive mechanisms and using evolutionary game theory to observe the behavior of all parties, it adapts to situations where decision makers are not completely rational in the real world [21,22]. At present, evolutionary game theory has been widely applied to study stakeholders' decision-making behavior in the building energy conservation field [23]. The dynamic equations of tripartite games are derived from the foundation of evolutionary game theory [24]. To construct a reasonable game between the government, enterprises, and farmers and to study the evolution of strategies and interest issues among these three stakeholders, the construction of the dynamic equation of the tripartite game needs to meet the following three assumptions:

(1) Assumption of bounded rationality. In the tripartite evolutionary game model of passive housing, the government, enterprises, and farmers are the three main players in the game, with incomplete information symmetry. During the game, participants continuously improved their game strategies based on their own benefits.
(2) Assumption of tripartite game strategy. The set of game strategies of the government was S1 (promoting passive housing or not promoting passive housing), the set of game strategies for enterprises was S2 (supporting passive housing or not supporting passive housing), and the set of game strategies for farmers was S3 (cooperating with passive housing or not cooperating with passive housing).
(3) Assumption of the initial state of the game. At the beginning of the game, the probability of the government "promoting passive housing" was x ($0 < x < 1$), and the probability of it "not promoting passive housing" was $1 - x$. The probability of enterprises "supporting passive housing" was y ($0 < y < 1$), and the probability of "supporting traditional housing" was $1 - y$. The probability of farmers "cooperating with the completion of passive housing" was z ($0 < z < 1$), and the probability of "cooperating with the completion of traditional housing" was $1 - z$. Here, x, y and z were functions of time t, and x, y and $z \in [0, 1]$.

The specific parameters involved in the game model are shown in Table 1. Based on the appeal assumptions and Table 1, the evolutionary game benefit matrix of the government, enterprises, and farmers can be obtained, as shown in Table 2.

Table 1. Game model parameters.

Parties	Parameters
Government	The benefit obtained by the government is A [10] The cost of government investment is B [10] The reward for enterprises supporting passive housing is Ca1 [17] The penalty for enterprises supporting traditional housing is Cb1 [17] The government subsidy coefficient for enterprises and farmers to choose passive housing is O (0 < O < 1) [17] The penalty coefficient for enterprises and farmers not choosing passive housing is S (0 < S < 1) [17]
Enterprises	The government profit when enterprises support and farmers cooperate with traditional housing construction is De1 [25,26] The additional profit for the government when enterprises support and farmers cooperate with the construction of passive housing is De2 [24,25] The benefit obtained by enterprises to support the construction of traditional housing is Ef1 [27,28] The additional benefit of supporting the construction of passive housing by enterprises is Ef2 [27,28] The cost paid by enterprises to support the construction of traditional housing is Gh1 [27] The additional cost paid by enterprises to support the construction of passive housing is Gh2 [27]
Farmers	The benefit of farmers in cooperation with the construction of traditional houses is I1 [29,30] The additional benefit from the construction of passive houses by farmers is I2 [29] The cost paid by farmers to cooperate with the construction of traditional housing is J1 [29,30] The additional cost paid by farmers to cooperate with the construction of passive houses is J2 [29,30]

Table 2. Evolutionary game benefit matrix of government, enterprises, and farmers.

Government	Construction	Farmers	
		Cooperating with the Completion of Passive Housing	**Cooperating with the Completion of Traditional Housing**
Promoting	Supporting passive housing	Government benefit: $X_1 = A - Ca1 - B + De1 + De2$ Enterprise benefit: $Y_1 = (1 - O) * Ca1 + Ef1 + Ef2 - Gh1 - Gh2$ Farmer benefit: $Z_1 = O * Ca1 - J1 - J2 + I1 + I2$	Government benefit: $X_2 = A - Ca1 - B + De1 + De2$ Enterprise benefit: $Y_2 = Ca1 + Ef1 + Ef2 - Gh1 - Gh2$ Farmer benefit: $Z_2 = 0$
	Supporting traditional housing	Government benefit: $X_3 = A + Cb1 - B + De1$ Enterprise benefit: $Y_3 = -Cb1 + Ef1 - Gh1$ Farmer benefit: $Z_3 = 0$	Government benefit: $X_4 = A + Cb1 - B + De1$ Enterprise benefit: $Y_4 = -(1 - S) * Cb1 + Ef1 - Gh1$ Farmer benefit: $Z_4 = -S * Cb1 + I1 - J1$
Not promoting	Supporting passive housing	Government benefit: $X_5 = De1 + De2$ Enterprise benefit: $Y_5 = Ef1 + Ef2 - Gh1 - Gh2$ Farmer benefit: $Z_5 = -J1 - J2 + I1 + I2$	Government benefit: $X_6 = De1 + De2$ Enterprise benefit: $Y_6 = Ef1 + Ef2 - Gh1 - Gh2$ Farmer benefit: $Z_6 = 0$
	Supporting traditional housing	Government benefit: $X_7 = De1$ Enterprise Benefits: $Y_7 = Ef1 - Gh1$ Farmer benefit: $Z_7 = 0$	Government benefit: $X_8 = De1$ Enterprise benefits: $Y_8 = Ef1 - Gh1$ Farmer benefit: $Z_8 = I1 - J1$

2.2. The Replicator Dynamic Equation of Stakeholders

Based on the benefit matrix above, when the government chooses the "promoting (the probability is "x" (0 < x < 1))" and "not promoting (the probability is "1 − x")" strategy, the expected government benefits are $E11$ and $E12$, respectively, with an average expected benefit of $\bar{E}1$. It can be seen that:

$$E11 = y * z * X_1 + y * (1 - z) * X_2 + (1 - y) * z * X_3 + (1 - y) * (1 - z) * X_4 \tag{1}$$

$$E12 = y * z * X_5 + y * (1 - z) * X_6 + (1 - y) * z * X_7 + (1 - y) * (1 - z) * X_8 \tag{2}$$

$$\begin{aligned} \bar{E}1 &= x * E11 + (1 - x) * E12 \\ &= De1 + A * x - B * x + Cb1 * x + De2 * y - Ca1 * x * y - Cb1 * x * y \end{aligned} \tag{3}$$

From this, it can be concluded that the replicator dynamic equation of government behavior strategy is:

$$\begin{aligned} F(X) &= \frac{dx}{dt} \\ &= x * \left(E11 - \bar{E}1\right) = x * (x - 1) * (B - A - Cb1 + Ca1 * y + Cb1 * y) \end{aligned} \tag{4}$$

Assuming that when enterprises choose the strategies of "supporting passive housing (the probability is "y" (0 < y < 1))" and "supporting traditional housing (the probability is "1 − y")", the expected benefits of the enterprises are E21 and E22, respectively, and the average expected benefit is $\bar{E}2$, which can be obtained as:

$$E21 = x * z * Y_1 + x * (1 - z) * Y_2 + (1 - x) * z * Y_5 + (1 - x) * (1 - z) * Y_6 \tag{5}$$

$$E22 = x * z * Y_3 + x * (1 - z) * Y_4 + (1 - x) * z * Y_7 + (1 - x) * (1 - z) * Y_8 \tag{6}$$

$$\begin{aligned} \bar{E}2 &= y * E21 + (1 - y) * E22 \\ &= Ef1 - Gh1 - Cb1 * x + Ef2 * y - Gh2 * y + Cb1 * s * x + Ca1 * x * y + Cb1 * x * y \\ &-Cb1 * s * x * y - Cb1 * s * x * z - Ca1 * o * x * y * z + Cb1 * s * x * y * z \end{aligned} \tag{7}$$

From this, it can be concluded that the replicator dynamic equation of enterprise behavior strategy is [31]:

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y * \left(E21 - \bar{E}2\right) \\ &= -y * (y - 1) * (Ef2 - Gh2 + Ca1 * x + Cb1 * x - Cb1 * S * x - Ca1 * O * x * z + Cb1 * S * x * z) \end{aligned} \tag{8}$$

Assuming that when farmers choose the strategies of "cooperating with passive housing (the probability is "z" (0 < z < 1))" and "cooperating with traditional housing (the probability is "1 − z")", the expected benefits for the farmers are E31 and E32, respectively, and the average expected benefit is Ē3, which can be obtained as:

$$E31 = x * y * Z_1 + x * (1 - y) * Z_3 + (1 - x) * y * Z_5 + (1 - x) * (1 - y) * Z_7 \tag{9}$$

$$E32 = x * y * Z_2 + x * (1 - y) * Z_4 + (1 - x) * y * Z_6 + (1 - x) * (1 - y) * Z_8 \tag{10}$$

$$\begin{aligned} \bar{E}3 &= z * E31 + (1 - z) * E32 \\ &= z * (x * y * (I1 + I2 - J1 - J2 + Ca1 * O) - y * (x - 1) * (I1 + I2 - J1 - J2)) \\ &-((I1 - J1) * (x - 1) * (y - 1) + x * (y - 1) * (J1 - I1 + Cb1 * S)) * (z - 1) \end{aligned} \tag{11}$$

Therefore, it can be concluded that the replicator dynamic equation of farmer behavior strategy is:

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z * \left(E31 - \bar{E}3\right) \\ &= -z * (z - 1) * (\mathrm{J1 - I1 + 2 * I1 * y + I2 * y - 2 * J1 * y - J2 * y + Cb1 * S * x} \\ &\mathrm{+Ca1 * O * x * y - Cb1 * S * x * y}) \end{aligned} \tag{12}$$

The replicator dynamic Equations (4), (8), and (12) of the government, enterprises, and farmers constitute a three-dimensional dynamic system, as shown in the set of Equation (13).

$$\begin{cases} F(X) = x * (x - 1) * (B - A - Cb1 + Ca1 * y + Cb1 * y) \\ F(y) = -y * (y - 1) * \begin{pmatrix} Ef2 - Gh2 + Ca1 * x + Cb1 * x - Cb1 * S * x \\ -Ca1 * O * x * z + Cb1 * S * x * z \end{pmatrix} \\ F(z) = -z * (z - 1) * \begin{pmatrix} J1 - I1 + 2 * I1 * y + I2 * y - 2 * J1 * y - J2 * y \\ +Cb1 * S * x + Ca1 * O * x * y - Cb1 * S * x * y \end{pmatrix} \end{cases} \tag{13}$$

3. Analysis of the Evolution Pathways of the Tripartite Game

Firstly, the gradual stability of the government was analyzed. According to Equation (4), the first derivative of x is:

$$dF(x)/dx = (2x - 1) * (B - A - Cb1 + Ca1 * y + Cb1 * y).$$

$$\text{Let } G(y) = B - A - Cb1 + Ca1 * y + Cb1 * y,$$

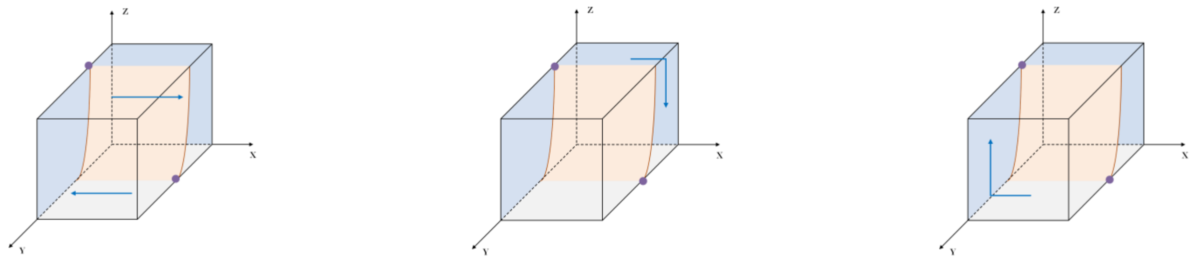
According to stability theory, for the government strategy (S1) of using passive housing to renovate new rural areas, the process of strategy adjustment tends to be stable only when $F(x) = 0$ and $dF(x)/dx < 0$ are simultaneously established. For ease of discussion,

$$\text{Let } y^* = \frac{A + Cb1 - B}{Ca1 + Cb1}.$$

There are two possible outcomes for the above issues:

(1) If $y = y^* = \frac{A+Cb1-B}{Ca1+Cb1}$, i.e., $G(y) = 0$, then $F(x) \equiv 0$. For any chosen value x here, the evolutionary system model remains in a stable state, as shown in Figure 2a.

(2) When $y \neq y^* = \frac{A+Cb1-B}{Ca1+Cb1}$, let $F(x) = 0$ to obtain two possible evolutionary stable points as $x = 0$ and $x = 1$.



$(a) y{=}y^* = \dfrac{A+Cb1-B}{Ca1+Cb1}$ $(b) y < y^* = \dfrac{A+Cb1-B}{Ca1+Cb1}$ $(c) y > y^* = \dfrac{A+Cb1-B}{Ca1+Cb1}$

Figure 2. The dynamic evolution pathway of government strategy.

Regarding (2) and taking the derivative of $F(x)$, two results can be obtained:

(1) If $y < y^* = \frac{A+Cb1-B}{Ca1+Cb1}$, then $G(y) > 0$, therefore, $F'(x)|_{x=0} > 0$, $F'(x)|_{x=1} < 0$ $x = 1$ is an evolutionary stable point, which means that the government chooses to promote the strategy of passive housing as shown in Figure 2b.

(2) If $y > y^* = \frac{A+Cb1-B}{Ca1+Cb1}$, then $G(y) < 0$, therefore, $F'(x)|_{x=0} < 0$, $F'(x)|_{x=1} > 0$, and hence, $x = 0$ is an evolutionary stable point, which means that the government chooses not to promote the strategy of passive housing as shown in Figure 2c.

Secondly, the gradual stability of the enterprise is analyzed. According to Equation (8), the first derivative of enterprises (y) is:

$$\frac{dF(y)}{dy} = (1-2y) * (Ef2 - Gh2 + Ca1 * x + Cb1 * x - Cb1 * S * x - Ca1 * O * x * z + Cb1 * S * x * z)$$

Let $H(X) = Ef2 - Gh2 + Ca1 * x + Cb1 * x - Cb1 * S * x - Ca1 * O * x * z + Cb1 * S * x * z$,

According to stability theory, for the strategy (S2) of enterprises using passive housing for new rural renovation, the process of strategy adjustment tends to be stable only when $F(y) = 0$ and $dF(y)/dy < 0$ are simultaneously satisfied.

For the ease of discussion, let $x* = \frac{Ef2 - Gh2}{Cb1 * S + Ca1 * O * z - Cb1 * S * z - Ca1 - Cb1}$.

There are two possible outcomes for the above situation:

(1) If $x = x* = \frac{Ef2 - Gh2}{Cb1 * S + Ca1 * O * z - Cb1 * S * z - Ca1 - Cb1}$, i.e., $H(x) = 0$,

Then $F(y) \equiv 0$. For any chosen value of y here, the evolutionary system model remains in a stable state, as shown in Figure 3a.

(2) When $x \neq x* = \frac{Ef2 - Gh2}{Cb1 * S + Ca1 * O * z - Cb1 * S * z - Ca1 - Cb1}$, let $F(y) = 0$ to obtain two possible evolutionary stable points as $y = 0$ $y = 1$.

Regarding (2) and taking the derivative of $F(y)$, two results can be obtained:

If $x < x* = \frac{Ef2 - Gh2}{Cb1 * S + Ca1 * O * z - Cb1 * S * z - Ca1 - Cb1}$, then $H(x) > 0$, therefore, $F'(y)|_{y=0} > 0$, $F'(y)|_{y=1} < 0$, and hence, $y = 1$ is an evolutionary stable point, which means that enterprises choose to support the strategy of passive housing as shown in Figure 3b.

If $x > x* = \frac{Ef2 - Gh2}{Cb1 * S + Ca1 * O * z - Cb1 * S * z - Ca1 - Cb1}$, then $H(X) < 0$, therefore, $F'(y)|_{y=0} < 0$, $F'(y)|_{y=1} > 0$, and hence, $x = 0$ is an evolutionary stable point, which means that enterprises choose to support the strategy of traditional housing as shown in Figure 3c.

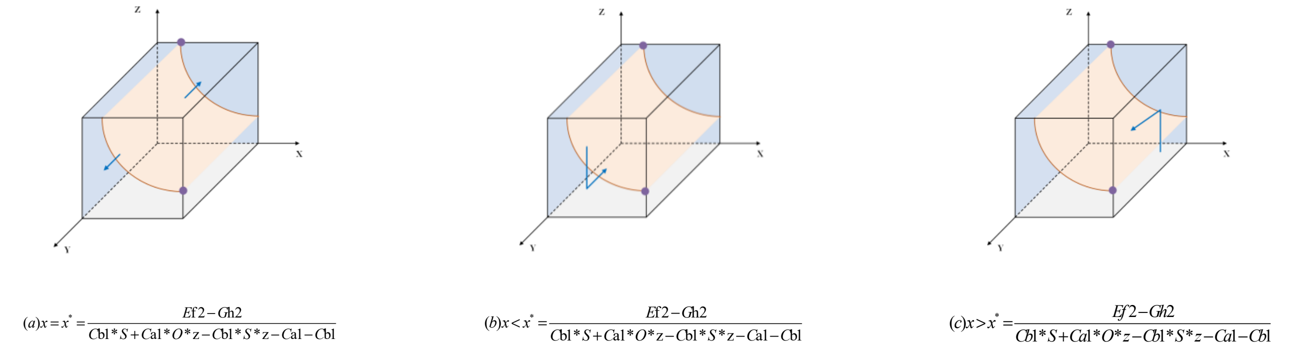


Figure 3. The dynamic evolution pathway of enterprise strategy.

Finally, the gradual stability of farmers was analyzed. According to Equation (12), the first derivative of farmers, z is:

$$dF(z)/dz = \mathrm{F}'(z)$$
$$= (1-2\mathrm{z}) * (\mathrm{J1} - \mathrm{I1} + 2 * \mathrm{I1} * \mathrm{y} + \mathrm{I2} * \mathrm{y} - 2 * \mathrm{J1} * \mathrm{y} - \mathrm{J2} * \mathrm{y} + \mathrm{Cb1} * \mathrm{S} * \mathrm{x} + \mathrm{Ca1} * \mathrm{O} * \mathrm{x} * \mathrm{y} - \mathrm{Cb1} * \mathrm{S} * \mathrm{x} * \mathrm{y}).$$

Let: $\mathrm{S(y)} = (\mathrm{J1} - \mathrm{I1} + 2 * \mathrm{I1} * \mathrm{y} + \mathrm{I2} * \mathrm{y} - 2 * \mathrm{J1} * \mathrm{y} - \mathrm{J2} * \mathrm{y} + \mathrm{Cb1} * \mathrm{S} * \mathrm{x} + \mathrm{Ca1} * \mathrm{O} * \mathrm{x} * \mathrm{y} - \mathrm{Cb1} * \mathrm{S} * \mathrm{x} * \mathrm{y})$.

According to the stability theory, it can be inferred that, for the farmers' strategy (S3) of using passive housing in the new rural renovation, the process of strategy adjustment tends to be stable only when $F(z) = 0$ and $dF(z)/dz < 0$ are simultaneously met. Hence, let $\mathrm{y}^* = \frac{I1 - J1 - Cb1 * S * x}{2 * I1 + I2 - 2 * J1 - J2 + Ca1 * O * x - Cb1 * S * x}$. There are two outcomes for the instances mentioned above:

(1) If $\mathrm{y} = \mathrm{y}^* = \frac{I1 - J1 - Cb1 * S * x}{2 * I1 + I2 - 2 * J1 - J2 + Ca1 * O * x - Cb1 * S * x}$, i.e., $S(y) = 0$,

then $F(\mathrm{z}) \equiv 0$. For any chosen value of z here, the evolutionary system model remains in a stable state, as shown in Figure 4a.

(2) When $\mathrm{y} \neq y^* = \frac{I1 - J1 - Cb1 * S * x}{2 * I1 + I2 - 2 * J1 - J2 + Ca1 * O * x - Cb1 * S * x}$,

let $F(\mathrm{z}) = 0$ to obtain two possible evolutionary stable points as $z = 0$ and $z = 1$.

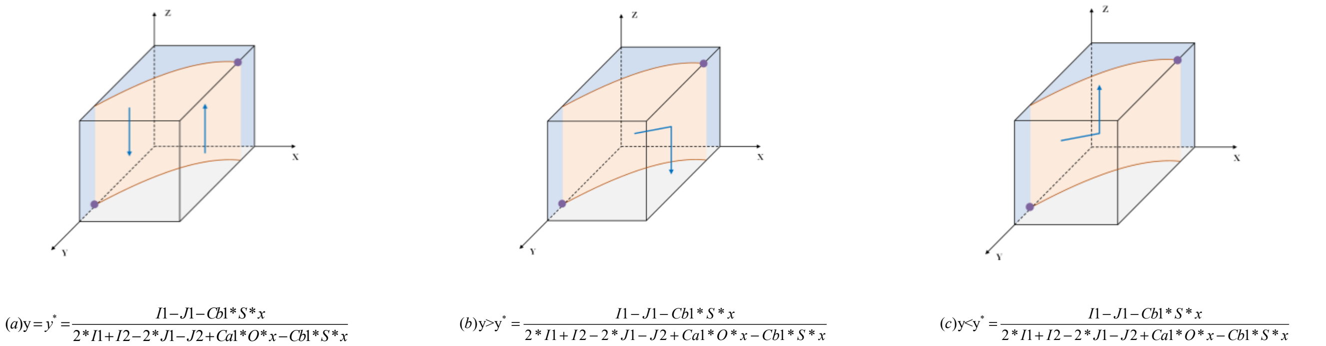


Figure 4. The dynamic evolution pathway of farmer strategy.

Regarding (2) and taking the derivative of $F(z)$, two results can be obtained:

If $\mathrm{y} > \mathrm{y}^* = \frac{I1 - J1 - Cb1 * S * x}{2 * I1 + I2 - 2 * J1 - J2 + Ca1 * O * x - Cb1 * S * x}$,

then $S(y) > 0$, therefore, $F'(z)|_{z=0} > 0$, $F'(z)|_{z=1} < 0$, and hence, $z = 1$ is an evolutionary stable point, which means that farmers choose to cooperate with the strategy of passive housing to implement rural renovation as shown in Figure 4b.

If $\mathrm{y} < \mathrm{y}^* = \frac{I1 - J1 - Cb1 * S * x}{2 * I1 + I2 - 2 * J1 - J2 + Ca1 * O * x - Cb1 * S * x}$, then $S(y) < 0$, therefore, $F'(Z)|_{Z=0} < 0$, $F'(Z)|_{Z=1} > 0$, and hence, $Z = 0$ is an evolutionary stable point, which means that farmers choose to corporate with the strategy of passive housing to implement rural renovation as shown in Figure 4c.

4. Solving for Nash Equilibrium and Stability Analysis of Equilibrium Points for the Tripartite Evolutionary Game

Let $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$. From Equation (13), it was determined that the system had eight (8) equilibrium points, which were: E1 (0, 0, 0), E2 (1, 0, 0), E3 (0, 1, 0), E4 (0, 0, 1), E5 (1, 1, 0), E6 (1, 0, 1), E7 (0, 1, 1), and E8 (1, 1, 1) [32].

From Equations (4), (8), and (12), the Jacobian matrix of the model was obtained, as shown in Equation (14).

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} (2*x-1)*(V+Z*y) & x*(x-1)*Z & 0 \\ y*(1-y)*(Z-M+N*z) & (1-2*y)*(G+(Q+E*z)*x) & y*(1-y)*(P*x-F*x) \\ z*(1-z)*(P+U*y) & z*(1-z)*(H+x*U) & (1-2*z)*(K+H*y+P*x+U*x*y) \end{bmatrix} \quad (14)$$

In which, only when the pure strategy Nash equilibrium is satisfied can the equilibrium point (EP) be asymptomatically stable [33,34]. In order to obtain the eigenvalues of each EP shown in Table 2, the EP was substituted into Equation (14). At the same time, reference was made to Lyapunov stability theory, that is, if all eigenvalues λ < 0, then the corresponding equilibrium point was stable, and that point was a stable strategy (ESS) [35]. Finally, the eigenvalues of the Jacobian matrix of the system were analyzed to verify the asymptotic stability of the EP [36], and the results are shown in Table 3.

Table 3. The eigenvalues of equilibrium points.

Equilibrium Point	Eigenvalue			Judgment Condition
	λ1	λ2	λ3	
$E_1(0,0,0)$	$A-B+Cb1$	$Ef2-Gh2$	$J1-I1$	$\lambda1<0, \lambda2<0, \lambda3<0$
$E_2(1,0,0)$	$-A+B-Cb1$	$Ca1+Cb1+Ef2-Gh2-Cb1*S$	$J1-I1+Cb1*S$	$\lambda1<0, \lambda2<0, \lambda3<0$
$E_3(0,1,0)$	$A-B-Cb1$	$Gh2-Ef2$	$I1+I2-J1-J2$	$\lambda1<0, \lambda2<0, \lambda3<0$
$E_4(0,0,1)$	$A-B+Cb1$	$Ef2-Gh2$	$I1-J1$	$\lambda1<0, \lambda2<0, \lambda3<0$
$E_5(1,1,0)$	$B-A+Ca1$	$Gh2-Cb1-Ef2-Ca1+Cb1*S$	$I1+I2-J1-J2+Ca1*O$	$\lambda1<0, \lambda2<0, \lambda3<0$
$E_6(1,0,1)$	$B-A-Cb1$	$Ca1+Cb1+Ef2-Gh2-Ca1*O$	$I1-J1-Cb1*S$	$\lambda1<0, \lambda2<0, \lambda3<0$
$E_7(0,1,1)$	$A-B-Ca1$	$Gh2-Ef2$	$J1-I2-I1+J2$	$\lambda1<0, \lambda2<0, \lambda3<0$
$E_8(1,1,1)$	$B-A+Ca1$	$Gh2-Cb1-Ef2-Ca1+Ca1*O$	$J1-I2-I1+J2-Ca1*O$	$\lambda1<0, \lambda2<0, \lambda3<0$

From a practical perspective, enterprises would not build passive housing on a large scale if there was no government incentive to promote passive housing. At the same time, without the support of enterprises, farmers would not use passive housing. Therefore, E1 (0, 0, 0), E3 (0, 1, 0), E4 (0, 0, 1), and E6 (1, 0, 1) were excluded here. Furthermore, according to the industry lifecycle theory, the lifecycle of passive housing used for rural renovation was divided into four stages: initial, growth, maturity, and stability. The corresponding ESS for the four lifecycle stages were E2 (1, 0, 0), E5 (1, 1, 0), E8 (1, 1, 1), and E7 (0, 1, 1), respectively. The stability conditions for each stage and their corresponding stability conditions are shown in Table 4 (detailed parameters for stability conditions can be found in Table 1) [37–39].

In Table 4, the significance expressed by the stability conditions of each stage was as follows: the government would choose to implement passive housing development policies when the benefits of the project exceeded the costs in stages E2, E5, and E8. In stage E7, if the benefits of implementing incentive measures were lower than the costs, the government would choose not to implement incentive measures and exit the entire market. When the benefit obtained by the enterprise in phase E2 was less than the cost, the enterprise would not support passive housing construction. However, the enterprise would support passive housing construction when the benefit obtained in phases E5, E8, and E7 was more significant than the cost. For farmers, if they choose traditional housing in phases E2 and E5, the benefit would be greater than the cost, so they would not choose passive housing during these phases. However, in phases E8 and E7, the benefit of choosing passive housing was more significant than the cost, so farmers would choose passive housing during these phases. And based on the high cost of passive housing itself and the characteristics of a long payback period, if E2, E5, and E8 do not meet the conditions of their respective phases of the first, that is, if the cost of input is far greater than the benefits, the government will withdraw from the entire project. If E5, E8, E7 do not meet the conditions of their respective stages of the second, that is, if the cost to the enterprise is greater than the profit, the enterprise will not cooperate with the implementation of the entire project. In E8 and E7, if condition three of the respective stage is not satisfied, i.e., if the benefits that farmers gain from passive housing are less than the costs they pay, farmers will choose not to accept passive housing.

Table 4. Stability conditions for equilibrium points in each stage.

Stage	Equilibrium Point	Stability Condition		
		Condition 1	Condition 2	Condition 3
Initial	$E_2(1,0,0)$	$B < A + Cb1$	$Ca1 + Ef2 < Gh2 + Cb1 * (S - 1)$	$J1 + Cb1*S < I1$
Growth	$E_5(1,1,0)$	$B < A - Ca1$	$Gh2 + Cb1 * (S - 1) < Ef2 + Ca1$	$I1 + I2 + Ca1 * O < J1 + J2$
Maturity	$E_8(1,1,1)$	$B < A - Ca1$	$Gh2 - Cb1 < Ef2 + Ca1 * (1 - O)$	$J1 + J2 < I2 + I1 + Ca1 * O$
Stability	$E_7(0,1,1)$	$B > A - Ca1$	$Gh2 < Ef2$	$J1 + J2 < I2 + I1$

5. Simulation of the Tripartite Game Model

In order to better observe the evolutionary trends of stakeholders in the use of passive housing for new rural renovation, Matlab R2021a was used to simulate an evolutionary game model. The evolutionary trends of three relevant participants under different strategies were observed, and market research and practical cases of passive housing reconstruction were used to determine the parameters in Table 1. The specific values are shown in Table 5 [10,17,28,40,41].

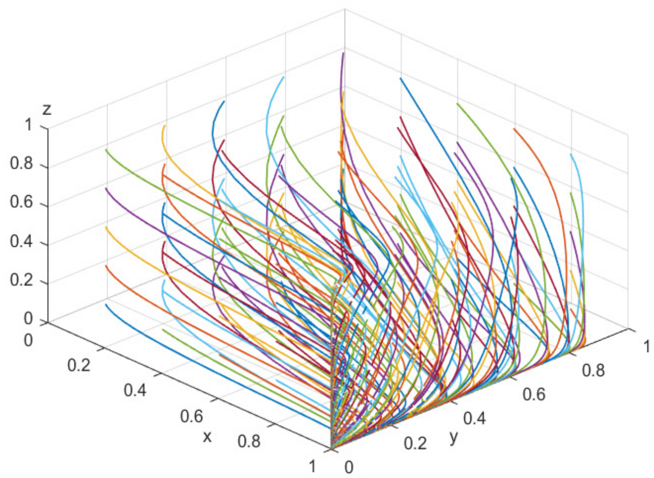
Table 5. Parameter values for each stage of the lifecycle.

Parameter	A	B	Ca1	Cb1	De1	De2	Ef1	Ef2	Gh1	Gh2	I1	I2	J1	J2	O	S
Initial stage	19	6	6	4	31	9	16	11	11	21	17	0	16	11	0.2	0.2
Growth stage	19	6	11	4	31	9	16	12	11	11	17	0	16	9	0.3	0.3
Maturity Stage	15	6	8	4	31	9	16	10	11	5	17	14	16	5	0.4	0.4
Stability stage	4	6	0	4	31	9	16	11	11	10	17	20	16	4	0.2	0.2

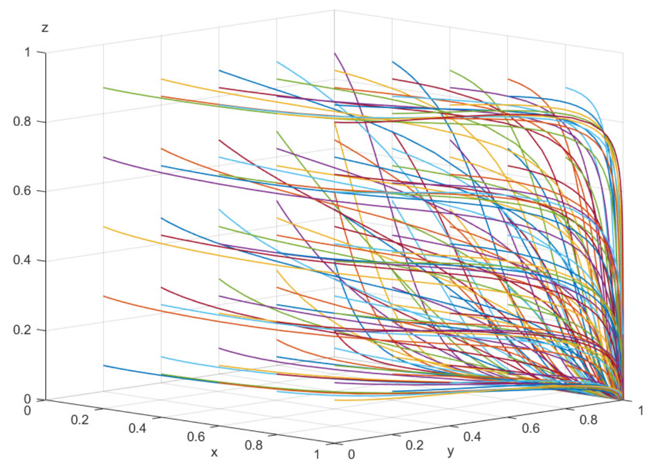
5.1. Analysis of Four-Stage Dynamic Evolutionary Results

The parameters in each of the four stages were set to different values, and each parameter value corresponds to the three stability conditions of this stage, as shown in Table 4. One hundred sets of three-way evolutionary game graphs with fixed x, y, and z were randomly generated [41], as detailed in Figure 5.

From Figure 5a, it can be seen that the model converges to E2 (1, 0, 0) after 100 iterative evolutions, validating that E2 (1, 0, 0) is an asymptotically stable EP (a). In this initial stage, the government adopts a strategy to promote passive housing development, with enterprises supporting traditional housing construction and farmers using traditional housing. In this situation, the government should provide professionals and expertise related to passive housing and develop rewards and penalties to promote passive housing development. At the same time, with government promotion, enterprises and rural households will also become familiar with passive housing. From Figure 5b, it can be seen that the model converges to E5 (1, 1, 0) after 100 iterative evolutions, which verifies that E5 (1, 1, 0) is an asymptotically stable EP (b). In this growth stage, the government promotes passive house development, enterprises support passive housing construction, and farmers use traditional housing. In this instance, the government should increase publicity efforts to make farmers aware of the advantages of passive housing, while strengthening supervision, penalties, and rewards for enterprises to encourage enterprises to support the construction of passive housing strongly. From Figure 5c, it can be seen that the model converges to E8 (1, 1, 1) after 100 iterations, verifying that E8 (1, 1, 1) is an asymptotically stable EP (c). In this maturity stage, no government action to promote passive housing, enterprises supporting passive housing construction, and farmers using traditional housing. As shown in Figure 5d, the model converges to E7 (0, 1, 1) after 100 iterations, verifying that E7 (0, 1, 1) is an asymptotically stable EP (d). At this stability stage, the government adopts a passive approach that does not support the development of passive housing, enterprises support the construction of passive housing, and farmers are accustomed to using traditional housing. At this point, enterprises and farmers need to continue cultivating the market, and the government should use indirect means to promote passive housing development, such as using online media to support the construction of passive housing.

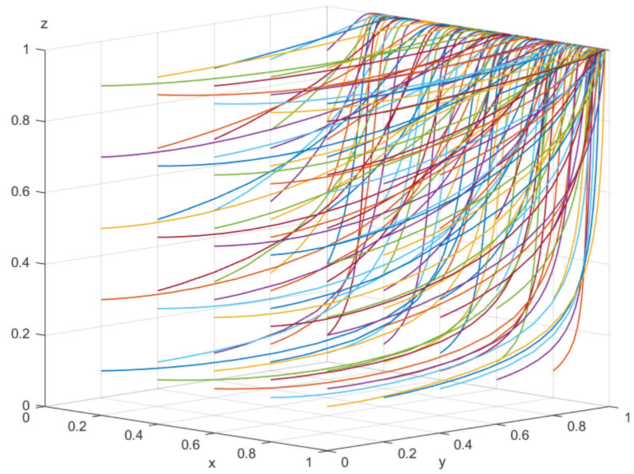


(**a**) Pathway of initial evolutionary stage

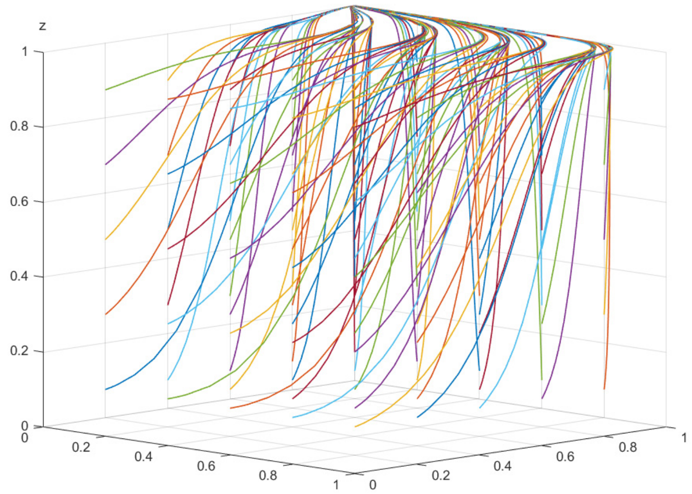


(**b**) Pathway of growth evolutionary stage

Figure 5. *Cont.*



(**c**) Pathway of maturity evolutionary stage



(**d**) Pathway of stability evolutionary stage

Figure 5. Dynamic evolution pathways in each stage.

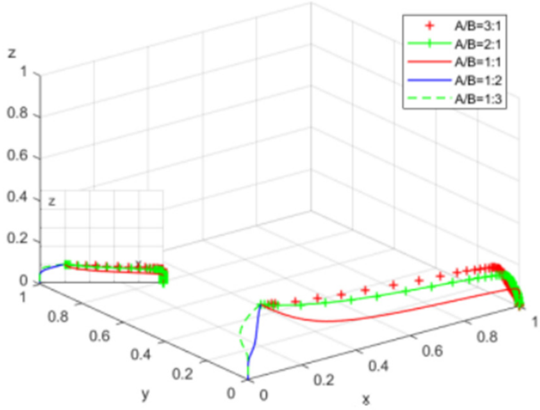
5.2. Sensitivity Analysis of Critical Parameters in the Evolution of Ternary Systems

To further explore the role of the government in promoting the development of passive housing, different numerical simulations were conducted on the (A:B), (Ca1:Cb1), and (O:S) stages of the government.

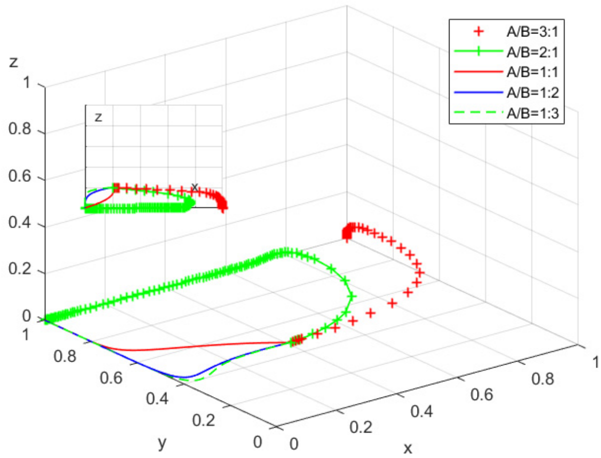
5.2.1. Comparative Sensitivity Analysis at Different Stages (A:B)

Based on the raw data of each stage, the values of government A:B in each stage were set to be 3:1, 2:1, 1:1, 1:2, and 1:3, respectively, and the sensitivity of the two parameters in each stage was analyzed. The simulation results are shown in Figure 6.

Figure 6 shows that, in the initial stage (a), when $A{:}B$ = 1:1 or $A{:}B$ = 3:1, 2:1, that is, the government's income A at this stage is greater than or equal to the cost B paid, the development trend of the three parties in the model conforms to the initial stage $E2\ (1,\ 0,\ 0)$. However, when the cost of government investment at this stage is greater than the benefit, that is, $A{:}B$ = 1:2 or $A{:}B$ = 1:3, the government should not choose to develop passive housing and should instead develop traditional housing. In the growth stage (b), only when $A{:}B$ = 3:1 does the development trend of the three parties in the model conform to the growth stage $E5\ (1,1,0)$. When $A{:}B$ = 2:1, the government's development trend tends to favor passive housing development in the early stages but tends to favor traditional housing development in the later stages. At *A*:*B* = 1:1, 1:2, 1:3, the government favors the development of traditional housing construction. In the maturity stage (c), when *A*:*B* = 3:1, 2:1, the development trend of the three parties in the model conformed to the maturity stage, $E8\ (1,\ 1,\ 1)$, and it was evident that the development trend of the model at *A*:*B* = 2:1 was significantly faster than that at *A*:*B* = 3:1. When *A*:*B* = 1:1, 1:2, 1:3, it is clear that the government's choice was not to support passive housing construction. In the stability stage (d), when *A*:*B* = 1:2, 1:3, the development trend of the three parties in the model conformed to the stability stage $E7\ (0,1,1)$, and it was also evident that when *A*:*B* = 1:2 , the development trend of the model was faster than *A*:*B* = 1:3. When *A*:*B* = 1:1, the government's strategic choice was not obvious; however, when *A*:*B* = 3:1, 2:1, the government's choice was clearly not to support traditional housing construction.

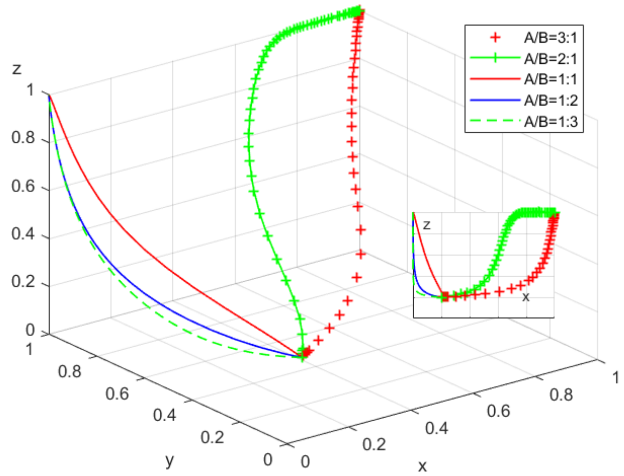


(**a**) Initial stage A: B trend

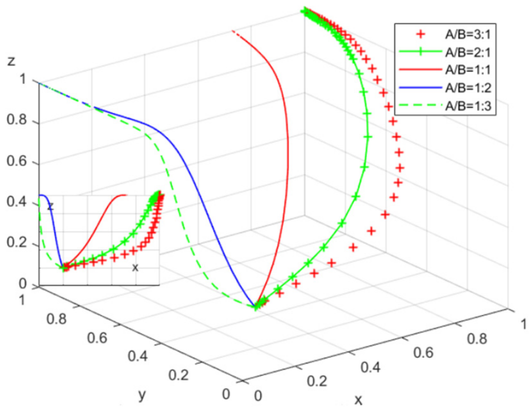


(**b**) Growth stage A: B trend

Figure 6. *Cont*.



(**c**) Maturity stage A: B trend



(**d**) Stability stage A:B trend

Figure 6. Trend graph of the ratio of A:B at different stages.

Because of the existence of passive housing 1. its own high construction costs; 2. payback period is too long; 3. domestic passive housing renovation market is immature; 4. lack of professional staff; 5. part of the scarcity of building materials and other characteristics. Therefore, "passive housing renovation" is different from general sustainable investment projects. Combining the characteristics of passive housing and the above analyses, it was suggested that the government's income, A, should always be greater than or equal to cost, B, from the initial stage to the maturity stage, which is beneficial for the development of this project. Therefore, the government needs to establish a cost–benefit plan aimed at promoting passive housing based on its economic situation. In the initial stage, the government's plan can appropriately increase investment costs according to the actual needs of real development. Doing so also implies allowing the investment costs to be on par with the benefits earned. In the growth stage, the government's benefits must be far greater than its investment costs. Otherwise, there is a risk of the government's strategic choices shifting towards the development of traditional housing construction. Therefore, at this stage, the government must establish an effective benefit–cost economic plan to protect its interests.

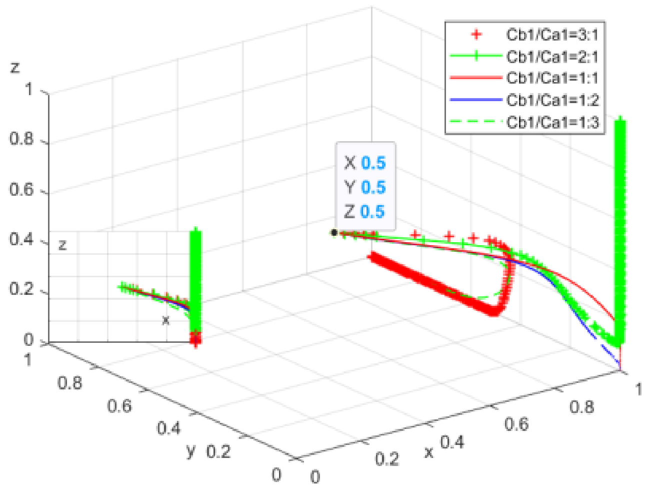
Furthermore, at this stage, the government needs to strictly monitor its own actions and the actions of enterprises to protect the entire process of passive housing implementation. In the maturity stage, the government can use a portion of the benefits to subsidize projects in order to expedite their progress. In the stability stage $E7\ (0, 1, 1)$, the larger the government's income A, the more the government's development trend regresses to the maturity stage $E8\ (1, 1, 1)$. When the benefit A is less than the cost B, the entire tripartite evolutionary process leans towards $E7\ (0, 1, 1)$, which is in line with the development of passive housing at this stage. However, the government's own interests are detrimental due to its loss. Hence, at this stage, the government needs to withdraw from the market and use other means to support the implementation of passive housing.

5.2.2. Comparative Sensitivity Analysis at Different Stages (Ca1/Cb1)

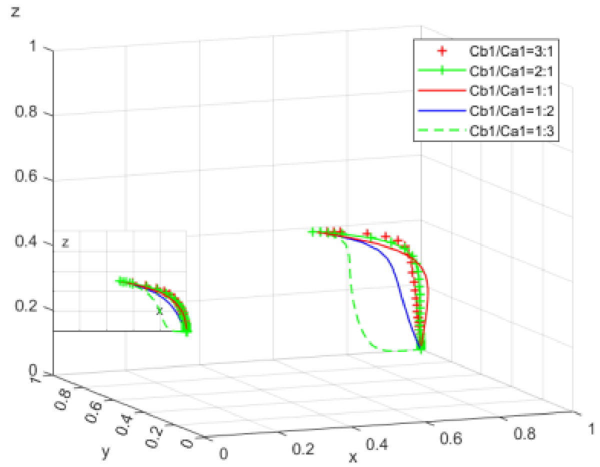
In order to more intuitively reflect the influence of the parameters, the initial values of x, y, and z were uniformly set to 0.5. Since the government was directly withdrawn from the entire market during the stability stage, the stability stage was not considered here. Based on the original data of $Ca1$ and $Cb2$ in each stage, the ratio of values in each stage was set as follows: $Cb1$:$Ca1$ = 3:1, 2:1, 1:1, 1:2, 1:3, so as to observe the influence of the two factors on the evolutionary trend of the model.

From Figure 7a, it can be seen that there is a very special phenomenon in the initial growth trend of the model. That is, when $Cb1$:$Ca1$ = 3:1 = 1:3, the tripartite evolutionary trend of the model was as follows: the government promotes passive housing construction, and enterprises support passive housing construction, but farmers choose to use traditional housing. This implies that the development trend of the model is to enter the next stage in advance, which is the growth stage $E5\ (1, 1, 0)$. When $Ca1$:$Cb1$ = 1:1 = 2:1, the tripartite evolutionary trend of the model conforms to $E2$ (1, 0, 0). In the growth stage (b), regardless of the situation of $Ca1 : Cb1$, the tripartite evolutionary trend of the model is consistent with the growth stage $E5\ (1, 1, 0)$. Finally, in the mature stage (c), when $Cb1$:$Ca1$ = 1:3, the tripartite development trend of the model is as follows: the government does not support passive housing construction, enterprises support passive housing construction, and farmers choose passive housing for living. This situation is consistent with the stable $E7\ (0, 1, 1)$. When $Cb1$:$Ca1$ = 2:1, 1:1, 1:2, 3:1, the tripartite evolutionary trend of the model conforms to the current maturity stage $E8\ (1, 1, 1)$.

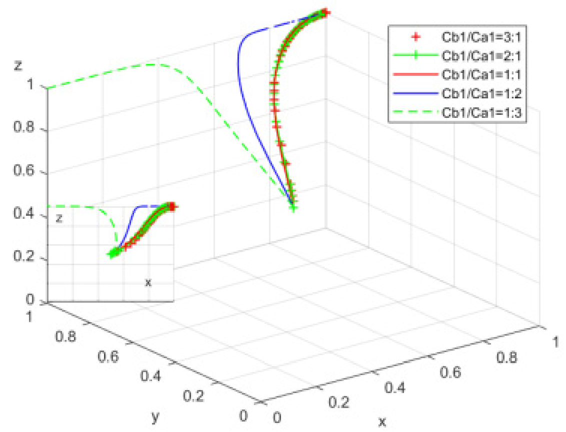
Based on the analysis above in this section, it is recommended that the government adopt a reward–penalty scheme, focusing on penalties and supplementary rewards to manage and guide enterprises in the initial stage. At this stage, the relevant laws and regulations are imperfect, and enterprises are bound to engage in illegal activities such as abuse of power for personal gain. At this time, the government needs to take punitive measures to strengthen enterprises' supervision and deter their illegal and irregular behavior. The penalties include the following: 1. Ordering the suspension of production and business; 2. Suspending or revoking licenses; 3. Restricting the carrying out of production and business activities; and 4. Placing enterprises on the list of enterprises in serious violation of the law and breach of trust. Punitive measures such as confiscation of illegal proceeds and illegal property and administrative detention may be applied to those who appear to have improperly colluded between the government and enterprises. At the same time, complementary reward measures can be used to incentivize enterprises to move towards supporting the construction of passive housing. During the growth and maturity stages, project development enters a formal stage, and legal and regulatory plans mature. A cumbersome penalty system may discourage companies from supporting projects. Therefore, it is recommended that the government adopt a scheme at this stage that is mainly based on rewards and supplemented by penalties. Incentives include rewards for pioneering enterprises that cooperate with passive house construction and substantial subsidies for enterprises involved in passive house retrofit projects. Government tax incentives for enterprises include reduction or exemption of corporate income tax and reduction or exemption of value-added tax. Financial support policies for enterprises include allowing low-interest loans and setting up project funds and industrial funds related to the project. However, at the same time, specific penalty measures need to be taken to avoid possible illegal acts of the government and enterprises at this project stage.



(**a**) Initial stage



(**b**) Growth stage

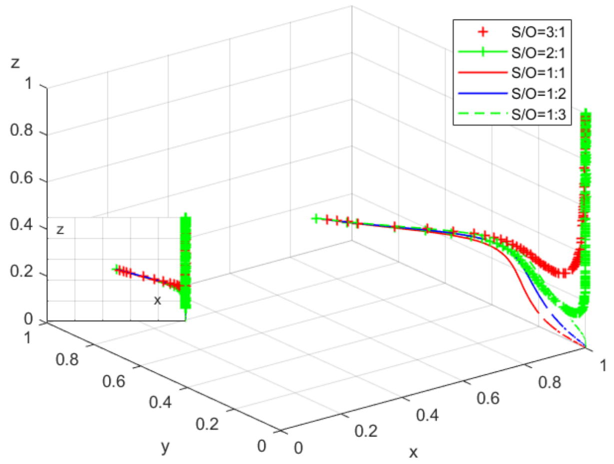


(**c**) Maturity stage

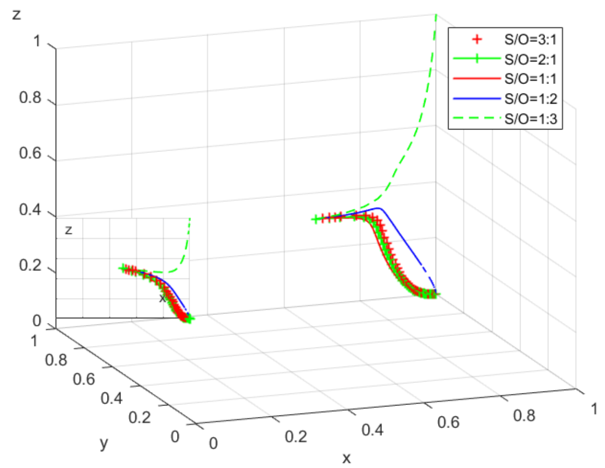
Figure 7. Trend graph of the ratio of Ca1:Cb1 at different stages.

5.2.3. The Evolutionary Trend of O:S at Different Stages

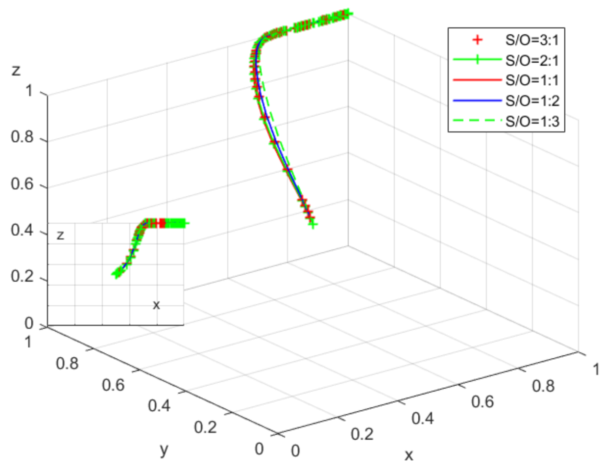
In order to more intuitively reflect the influence of parameters, the initial values of x, y, and z are uniformly set to 0.5 to discuss the evolutionary trend of O:S. Due to the withdrawal of the government from the entire market during the stability stage, the stability stage is not considered here. Based on the initial data of $O, S(O, S < 1)$ in each stage, the ratio of values in each stage is set as O:S = 3:1, 2:1, 1:1, 1:2, 1:3. To observe the impact of changes in two factors on the overall trend of the model evolution, the results are shown in Figure 8.



(**a**) Initial stage



(**b**) Growth stage



(**c**) Maturity stage

Figure 8. Trend graph of the ratio of O:S at different stages.

From Figure 8, it can be seen that in the initial stage (a), when *S*:*O* = 1:1, 1:2, 1:3, the tripartite evolutionary trend of the entire model conforms to the initial stage, $E2\ (1,0,0)$. In the growth stage (b), when *S*:*O* = 2:1,1:1,1:2, 1:3, the overall tripartite evolutionary trend of the model conforms to the growth stage of $E5\ (1,1,0)$. However, when *S*:*O* = 1:3 under the premise of government and enterprise support for passive housing construction, farmers will also choose to live in passive housing at this stage. Finally, at the maturity stage (c), regardless of the value of *O*:*S*, the overall tripartite evolutionary trend of the model conforms to the maturity stage $E8\ (1,1,1)$. Based on the analysis above, during the growth stage, it is recommended that the government appropriately increase the reward coefficient based on the original reward–penalty scheme. Doing so may accelerate the development process of passive housing renovation and construction.

5.2.4. Sensitivity Analysis of Individual Parameter Changes over a Fixed Stage

In the stability stage E7 (0, 1, 1), Ef2 was set to 1, 6, and 12 to observe the impact of this factor on the game. The results are shown in Figure 9. Which shows that when EF2 = 1 and EF2 = 6, the tripartite evolutionary trends of the model are (1, 0, 0), respectively. This indicates that if the benefits obtained by enterprises in passive housing at this stage are too small, they will no longer support the construction of passive housing, resulting in farmers choosing not to live in passive housing. However, when Ef2 = 12, the tripartite evolutionary trend of the model is (0, 1, 1); that is, enterprises and farmers continue to choose passive housing. This suggests that enterprises that support passive housing during the stability stage need to obtain decent benefits at this stage. When necessary, the government must provide ideal policy assistance and public opinion support to enterprises at this stage.

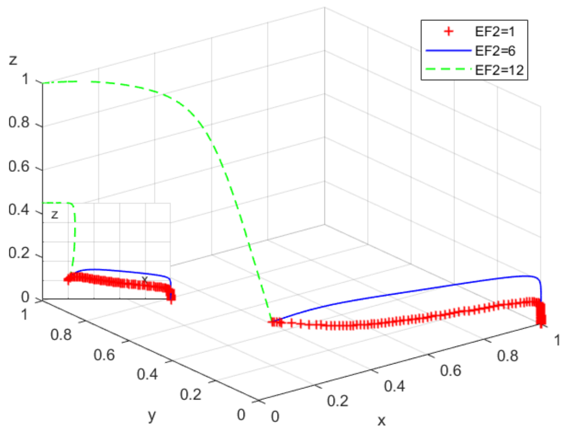


Figure 9. The effect of EF2 on the tripartite dynamic evolutionary trend.

In the stability stage E7 (0, 1, 1), I2 was set to 1, 2, and 4 to observe the impact of this factor on the game model. The results are shown in Figure 10. It can be seen that when I2 = 1 and I2 = 2, the tripartite evolutionary trend of the model is (0, 1, 0), respectively. This indicates that if farmers do not have a good experience when living in passive housing (such as poor living experience, lack of experience in passive housing, or high living costs), they will no longer live in passive housing. However, when I2 = 4, the tripartite evolutionary trend of the model is (0, 1, 1); that is, farmers continue to choose to use passive housing. Therefore, the government needs to pay attention to the actual use of passive housing in rural areas and whether it has brought real convenience and improved quality of life to farmers. Enterprises need to build passive housing that better meets the standards of farmers promptly, based on feedback from farmers.

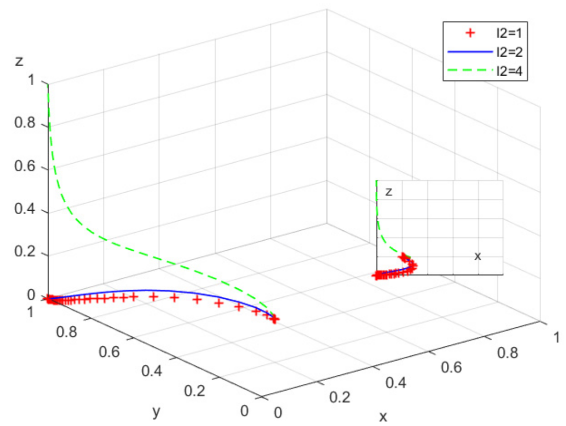


Figure 10. The effect of I2 on the tripartite dynamic evolutionary trend.

6. Conclusions

In this study, we provide an in-depth analysis of the strategic interactions and decision-making dynamics among the government, firms, and farmers by establishing a tripartite evolutionary game model for rural passive house construction. In addition, we further explore the government's strategy when the ratio of revenues to costs in the project varies; the results of the study found that when the revenues exceed the costs in the initial stage, the government will invest to stabilize the subsequent implementation and development, but as the government increases its investment and exceeds the costs or is equal to the costs, then the government will withdraw from the project. Secondly, when government penalties are greater than incentives, firms will tend to adopt this mechanism in the process, and farmers' interests will ultimately be safeguarded as firms implement it. This study, through a series of policies and market mechanisms to protect the interests of enterprises and farmers, ultimately promotes the widespread construction of passive houses.

In the current context of energy conservation and emission reduction in China, rural housing faces problems such as high energy consumption, low building quality, and low energy efficiency. Passive housing can significantly improve these problems, but the scale of its application in China is still very small, and the market associated with it is full of potential. China also lacks relevant policy documents. In this paper, we simulate the development of the passive house market for rural renovation based on evolutionary game theory and by taking into account a number of practical factors. The development process is divided into four phases: the initial phase, the growth phase, the maturity phase, and the stability phase; each phase is described and analyzed in detail. By modifying the parameters, the behavior of the government, enterprises, and farmers in the simulation is observed, and their optimal behavioral paths are analyzed. The simulation is a reference for the promotion of passive building and passive housing policies in China. It also provides suggestions for the future promotion of passive housing and related green and energy-saving buildings in China and the world.

Although a series of results and suggestions are made based on the simulation of the real situation, the parameter values are idealized and the contingencies are not taken into account. Therefore, there are still some gaps with the real situation. Moreover, this study only considered three stakeholders, namely, the government, enterprises, and farmers, and future studies may consider market audits and relevant building materials suppliers for a more comprehensive and in-depth discussion.

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